# R&D of AC-LGAD based 4D tracker

*with precision timing information for HL-LHC and the future colliders*

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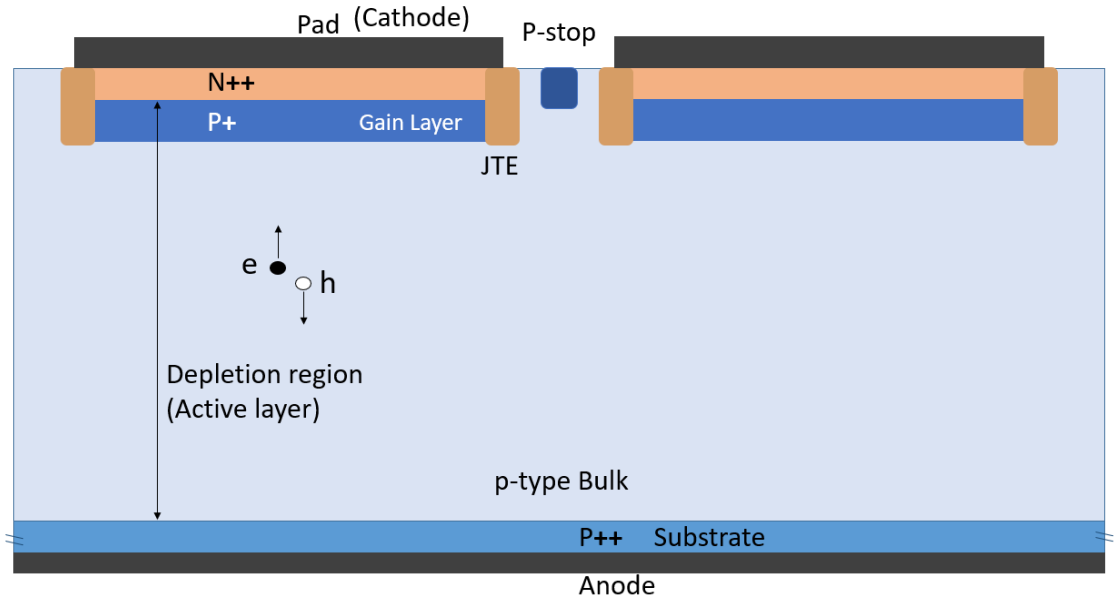
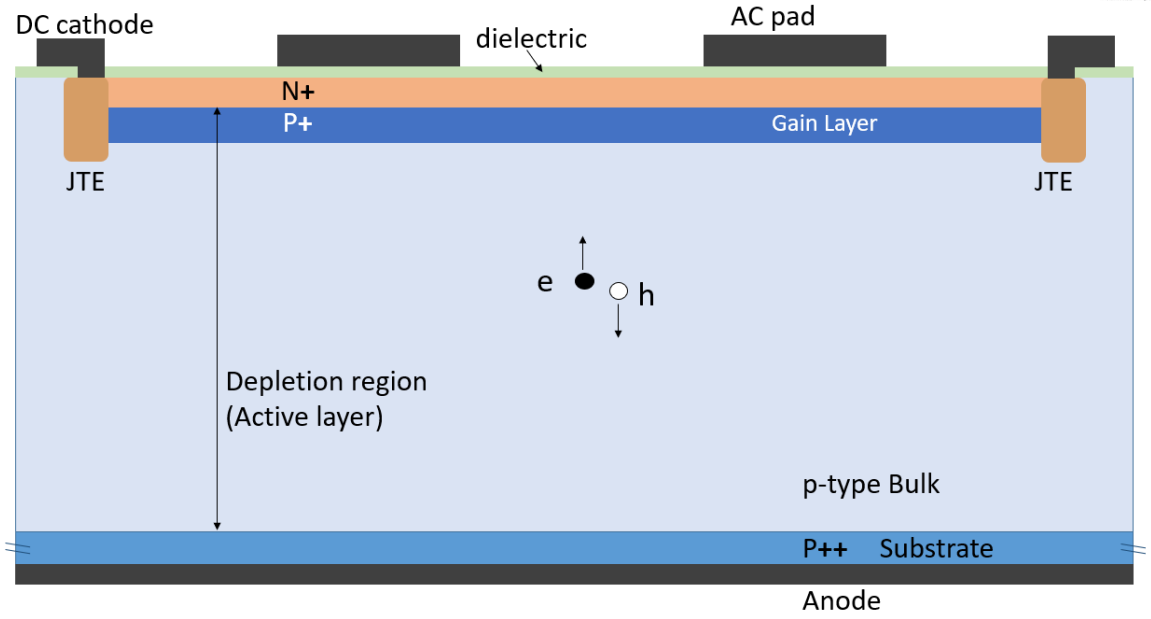
# 1. Introduction of AC-LGAD




**LGAD (Low-Gain Avalanche Diode)**

- The read-out electronics is connected to n++ layer
- Time resolution ~ 30ps
- Position resolution: pixel size/$\sqrt{12}$
- Radiation hardness： $10^{15}$ ~$10^{16}n_{eq}/cm^2$

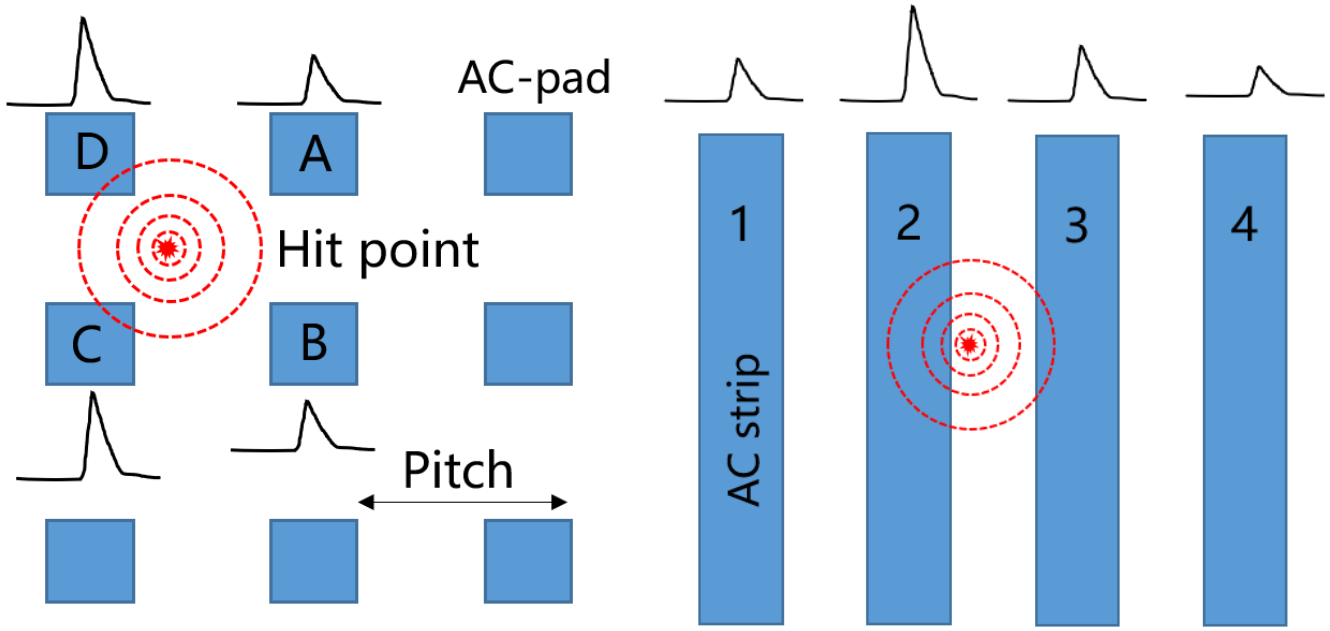



**AC-LGAD (AC-coupled LGAD)**

- Metal AC-pads separated from the n+ layer by a thin dielectric ($Si_3N_4$, $SiO_2$)
- no dead zone (100% fill factor)
- Time resolution ~ 30ps
- Position resolution: 5~10 um
- Radiation hardness： $10^{15}$ ~$10^{16}n_{eq}/cm^2$

# 1. Introduction of AC-LGAD

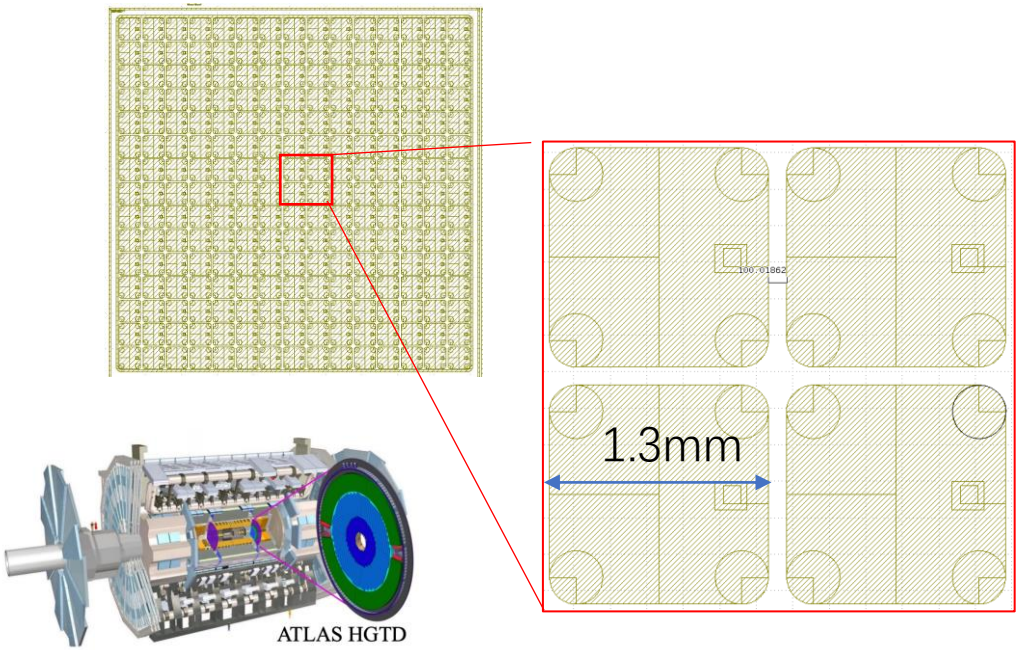
## AC-LGAD：two layout schemes for AC-pads




**Pixels AC-LGAD**:
- Position information：1 layer (x,y)
- Bump bonding

**Strips AC-LGAD**:
- Lower readout electronics，no bump bonding
- Position information：2 layers for (x,y)

## DC-LGAD:
## 15×15 LGAD for ATLAS HGTD project



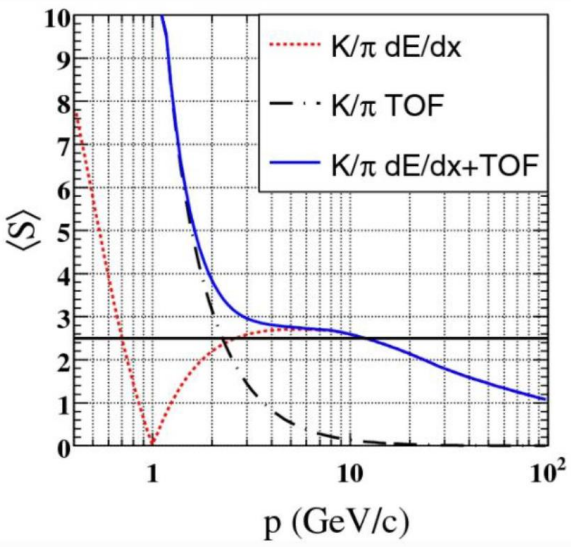

- **Dead zone : ~0.1mm**
- **Pixel size: 1.3mm**

Smaller Pixel LGADs -> Lower fill factor

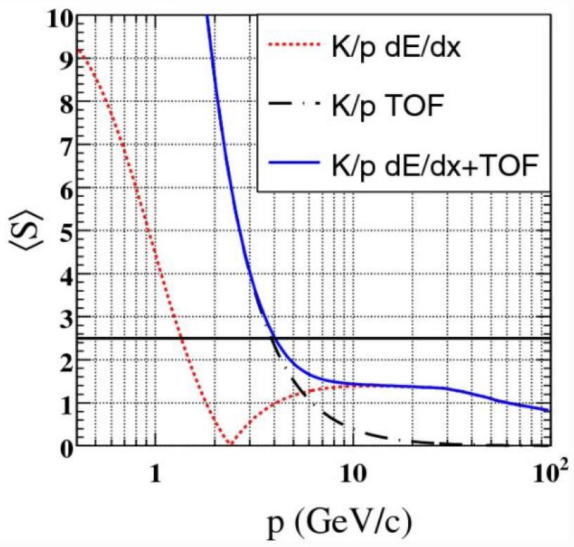
# 2. Application of AC-LGAD： CEPC timing detector

- **Circular Electron Positron Collider (CEPC) will produce $10^{12}$ Z boson at Z pole: Rich flavor physics program**
- **Particle separation problems** of Gas detector (dE/dx) for CEPC flavor physics:
  - **0.5-2 GeV for K/pi separation, >1.5 GeV for K/p separation**
- **CEPC International Advisory Committee: one of the key recommendations**
  Precision timing detector should be determined as a matter of urgency (4D track)
- **Timing detector is complementary to gas detector:** improves the separation ability
  **0 - 4 GeV** for K/pi separation, **0 – 8 GeV** for K/p separation
- **Concept design:** Offer the time and spatial information (4D track) Close to / replace SET tracker

**K/pi separation**

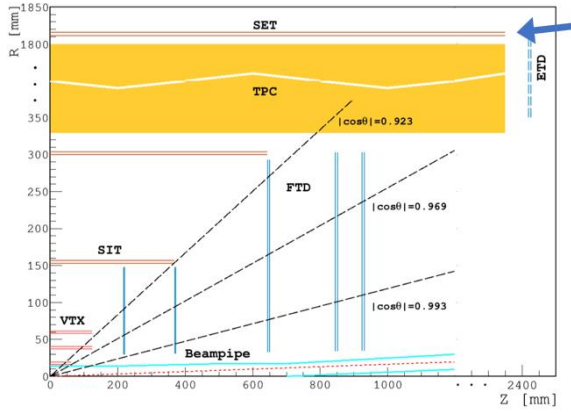



**K/p separation**

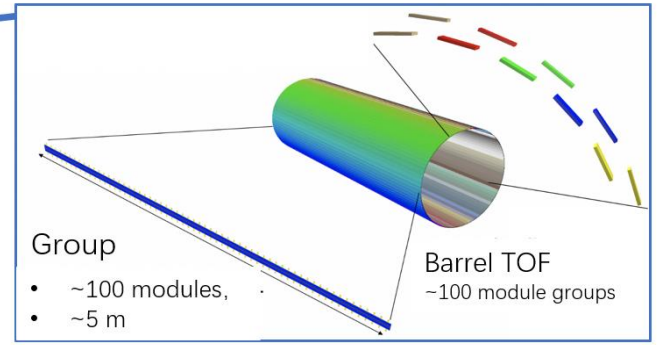



**CEPC LGAD timing detector concept designs**

**Baseline detector concept in CDR**

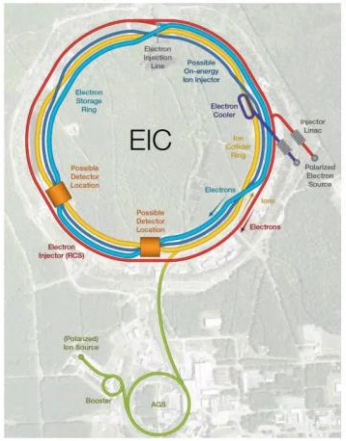



LGAD timing detector in Barrel region

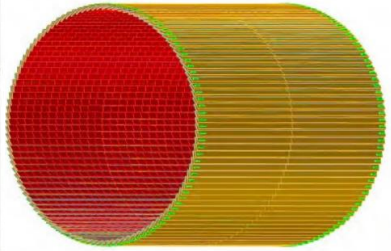


# 2. Application of AC-LGAD

**Electron-Ion Collider (EIC)**: Timing-tracker

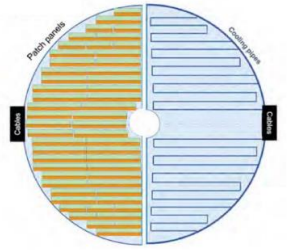



Barrel AC-LGAD detector



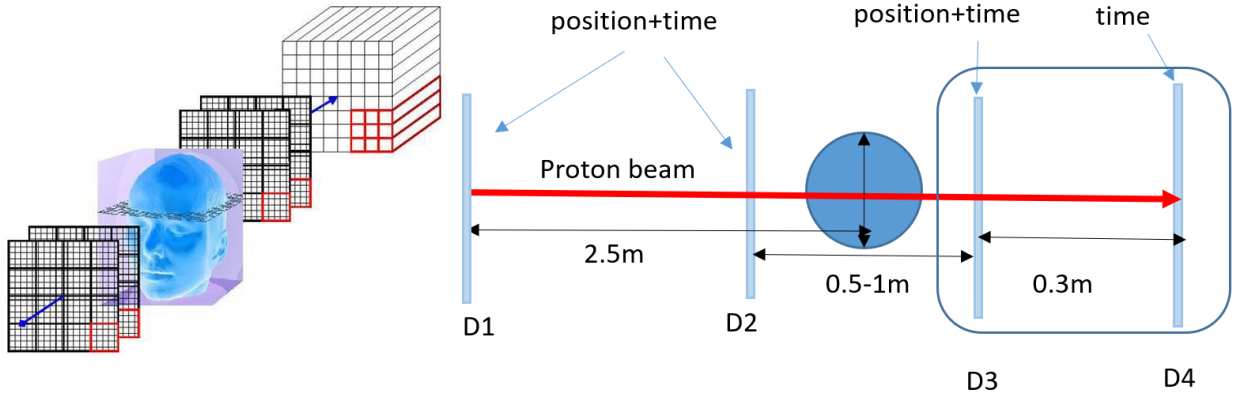
10.9 $m^2$

Hadron endcap AC-LGAD detector

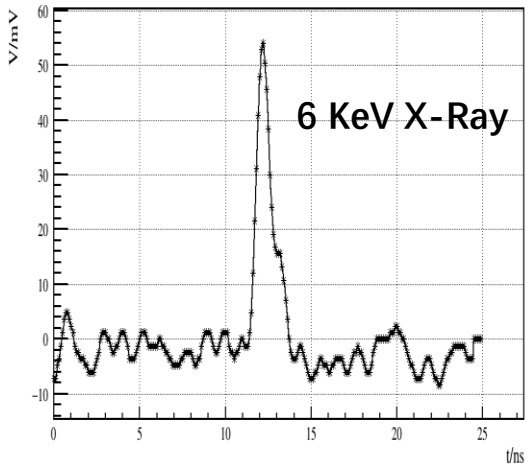


2.22 $m^2$

**Nuclear Medicine Instruments**:
Such as proton therapy and proton CT




**X-ray detectors** @ advanced light sources


## other applications

- Beam Telescope for Beam Test Platform
- LiDAR: Positioning and Navigation
- Track and time detectors in other particle physics and nuclear physics experiments
- …

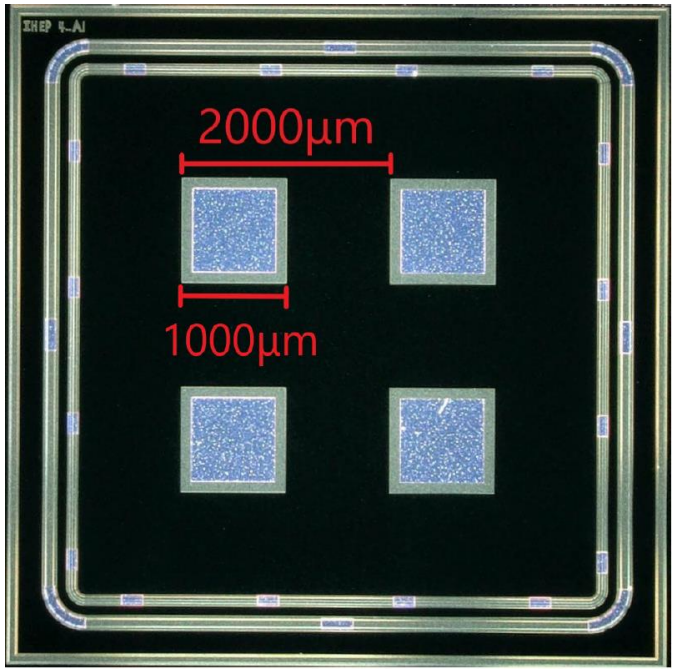
# 3. AC-LGAD sensors development by IHEP

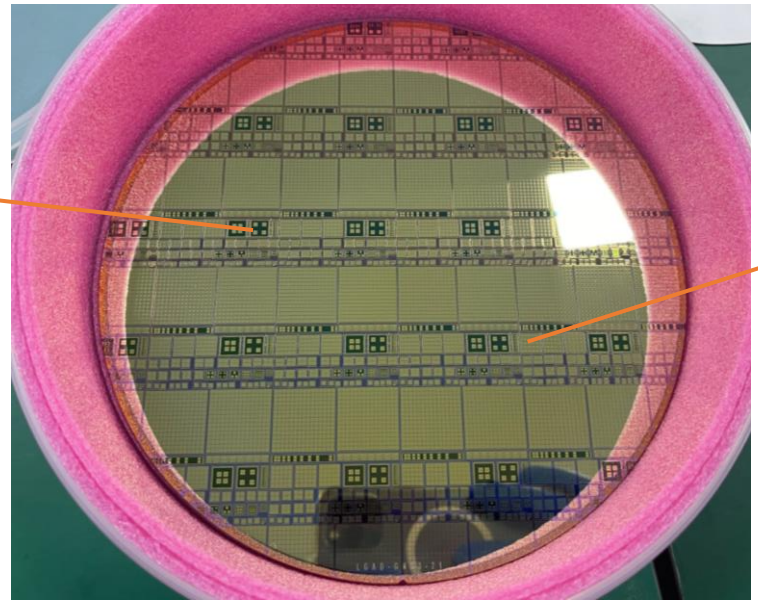
## Pixels AC-LGAD:

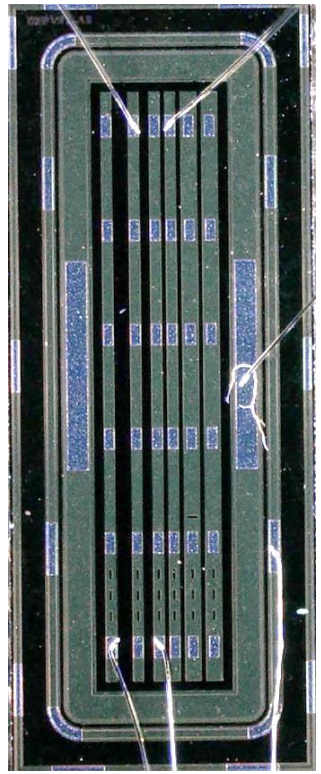
- Position information: 1 layer
- Pitch size 2000um, pad size 1000um
- Different N+ dose :
  - **10P, 5P, 1P, 0.5P, 0.2P**

## Strips AC-LGAD:

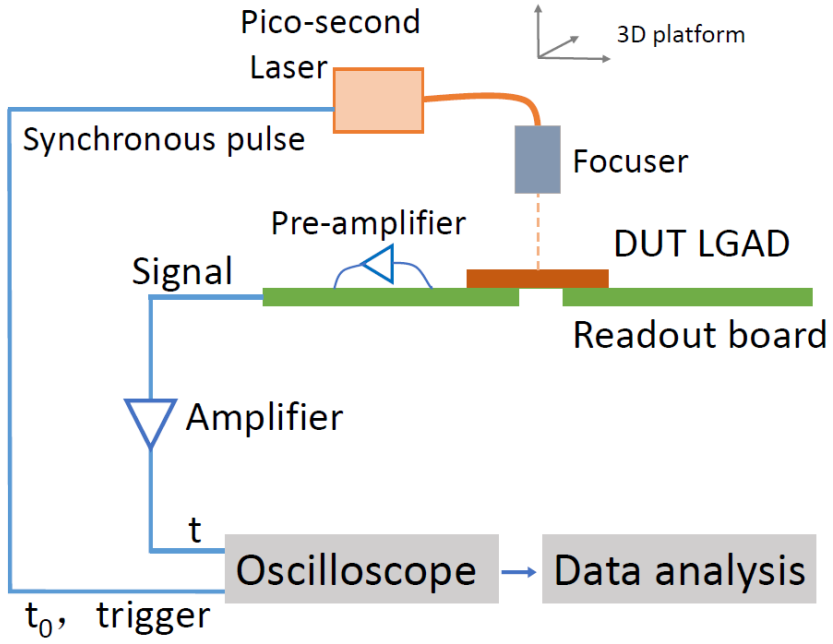
- Position information: 2 layer
- Strip length 5.6mm, width 100um
- Different Pitch size:
  - **150um、200um、250um**

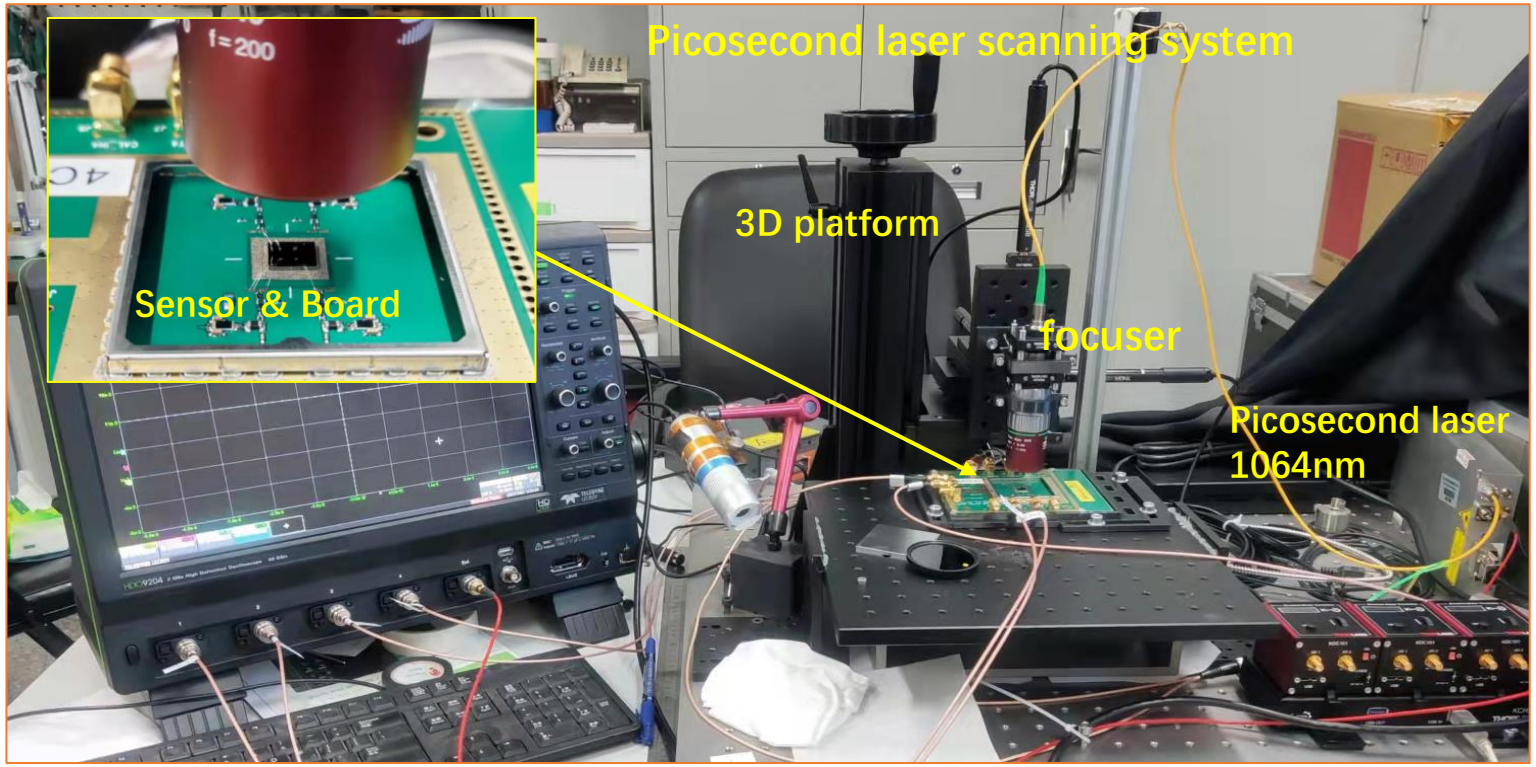


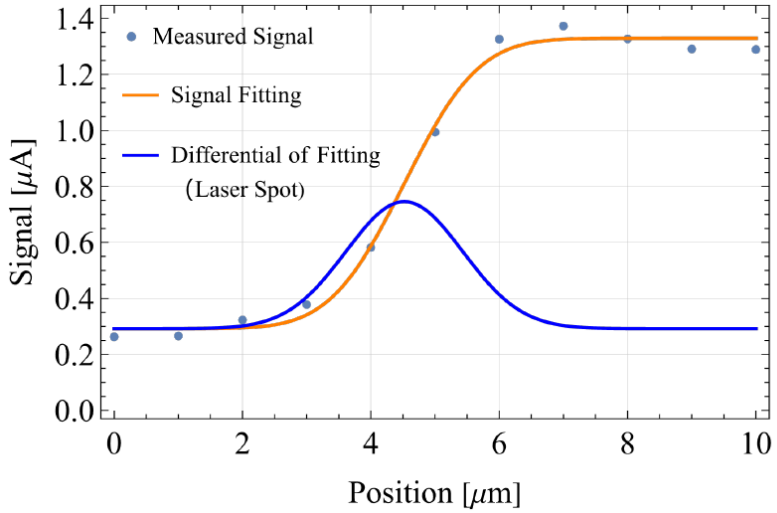





# 4. AC-LGAD sensor test： Picosecond Laser

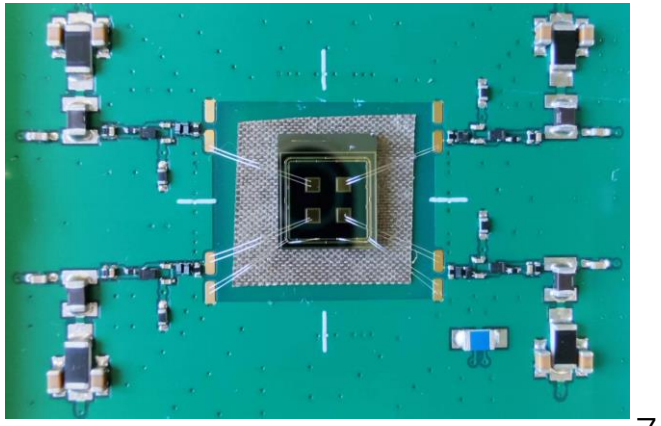


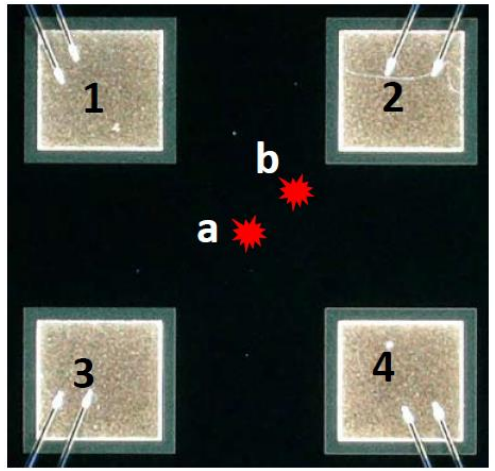



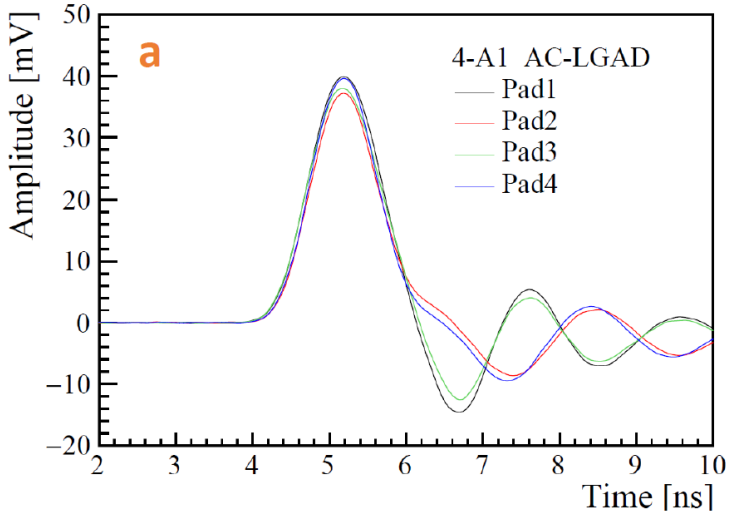

## Picosecond laser scanning system

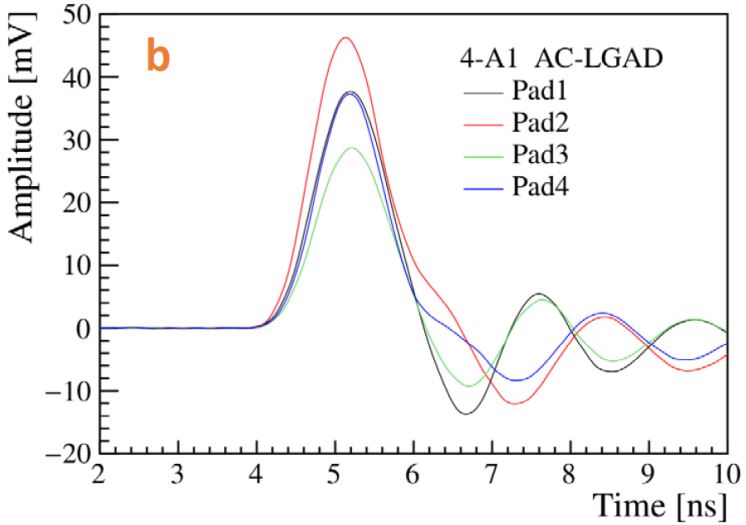
- Displacement accuracy 1 μm
- Automated scanning
- Picosecond laser 1064nm
- Spot size ~2μm



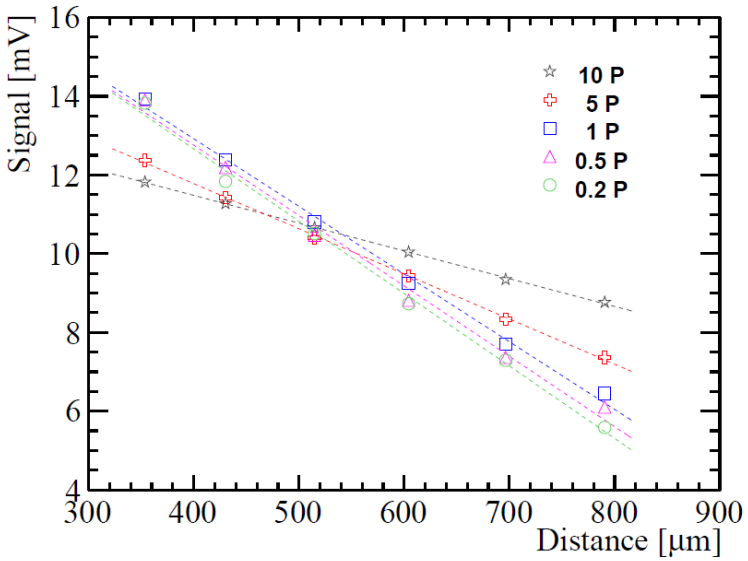
# 4. AC-LGAD sensor test： Signal attenuation



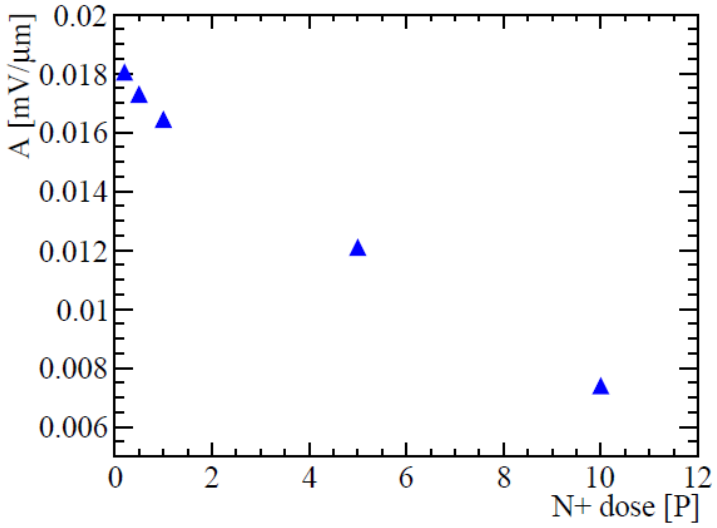




signal amplitude vs. distance



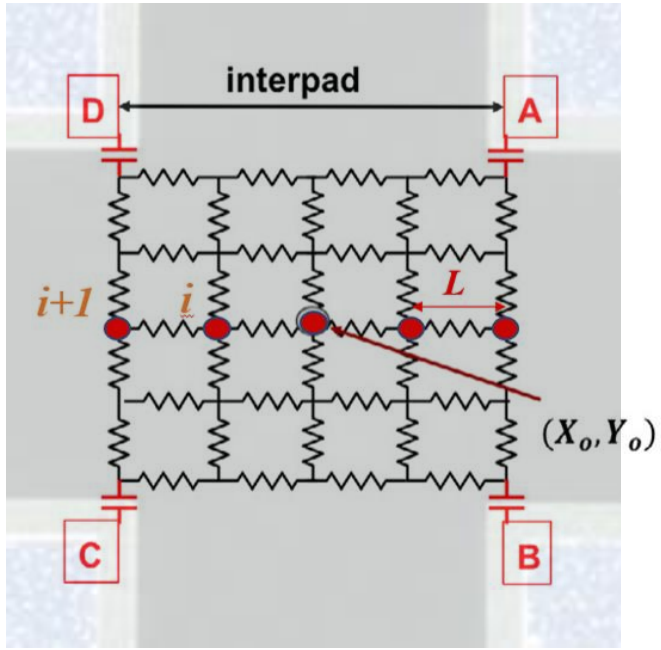

attenuation factor *A*



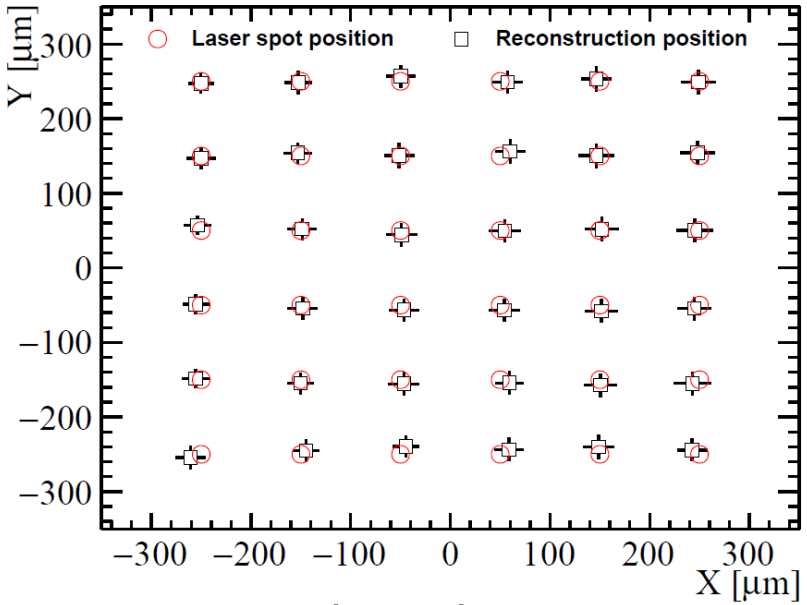

- The signal decreases with distance
- The factor *A* is obtained by the linear fit

- The *A* decreases with the increase of N+ dose
- Low N + dose means high resistivity

# 5. Position reconstruction： pixels AC-LGAD

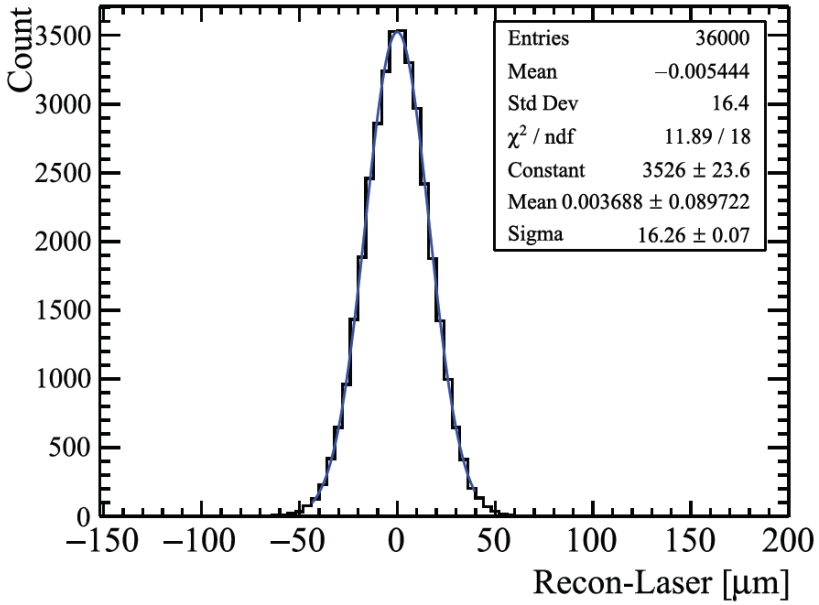



reconstructed 6x6 positions




Good consistency

**Spatial resolution：reconstruction - laser**




$$X = X_0 + k_x\left(\frac{q_A + q_B - q_C - q_D}{q_A + q_B + q_C + q_D}\right) = X_0 + k_x m$$

$$Y = Y_0 + k_y\left(\frac{q_A + q_D - q_B - q_C}{q_A + q_B + q_C + q_D}\right) = Y_0 + k_y n$$

Correction factor： $k_x$ $k_y$

$$k_x = L\frac{\sum(m_{i+1} - m_i)}{\sum(m_{i+1} - m_i)^2} \qquad k_y = L\frac{\sum(n_{i+1} - n_i)}{\sum(n_{i+1} - n_i)^2}$$

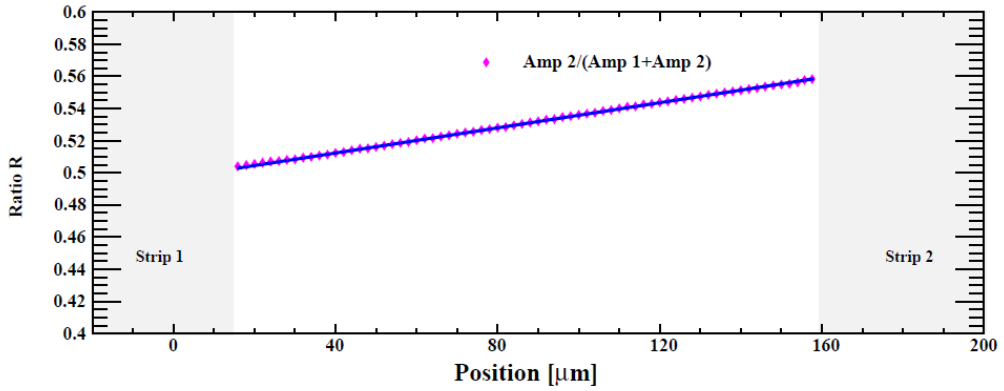
**Discretized Positioning Circuit model (DPC)**

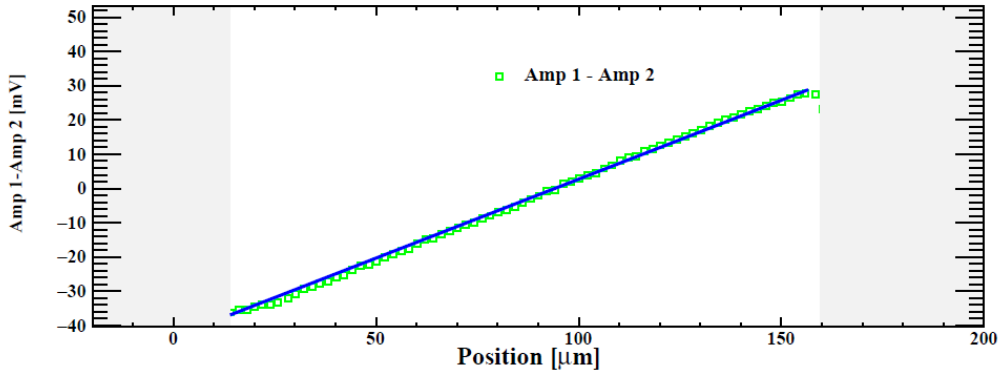
**Spatial resolution：**

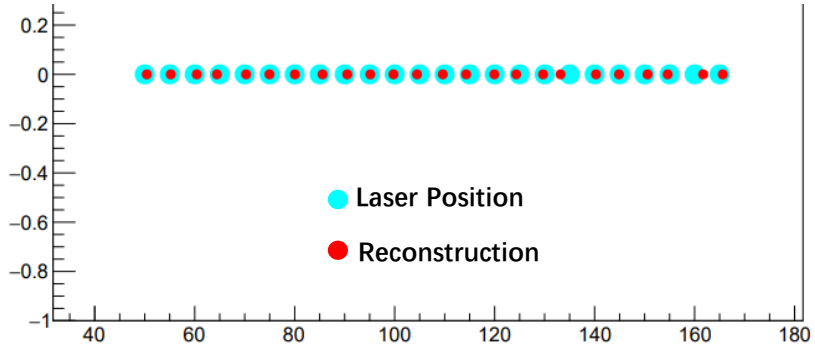
- the sigma of the difference between the laser and the reconstructed position

$$\sigma_{spatial} = \sigma_{reconstruction-laser}$$

# 5. Position reconstruction： strips AC-LGAD



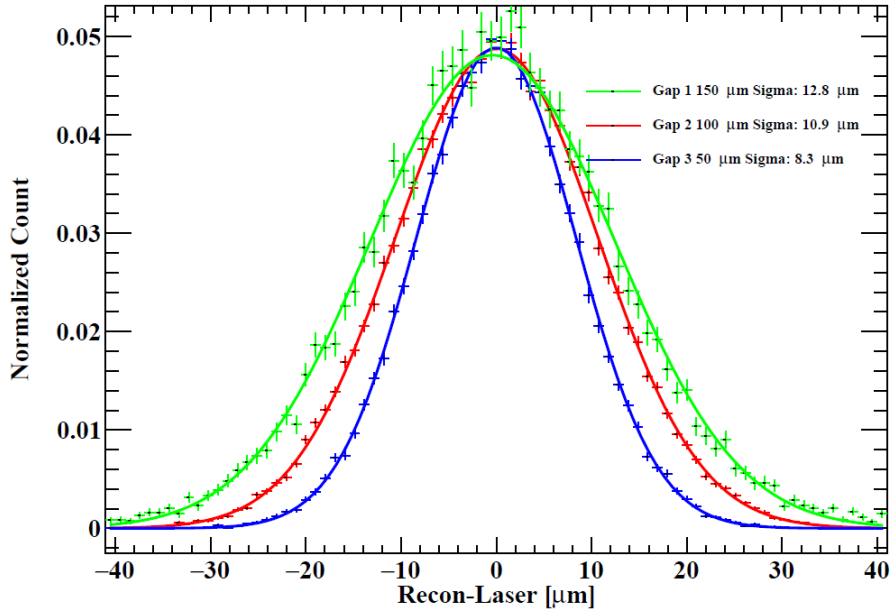




reconstructed positions

reconstructed position

$$R = \frac{Amp_2}{Amp_1 + Amp_2}$$

$$x = \frac{R - c}{k_R}$$

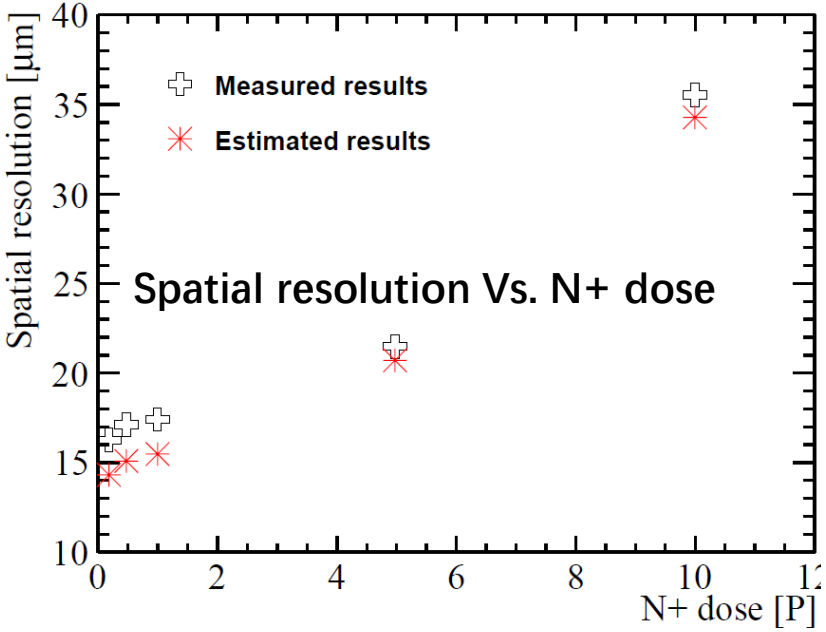


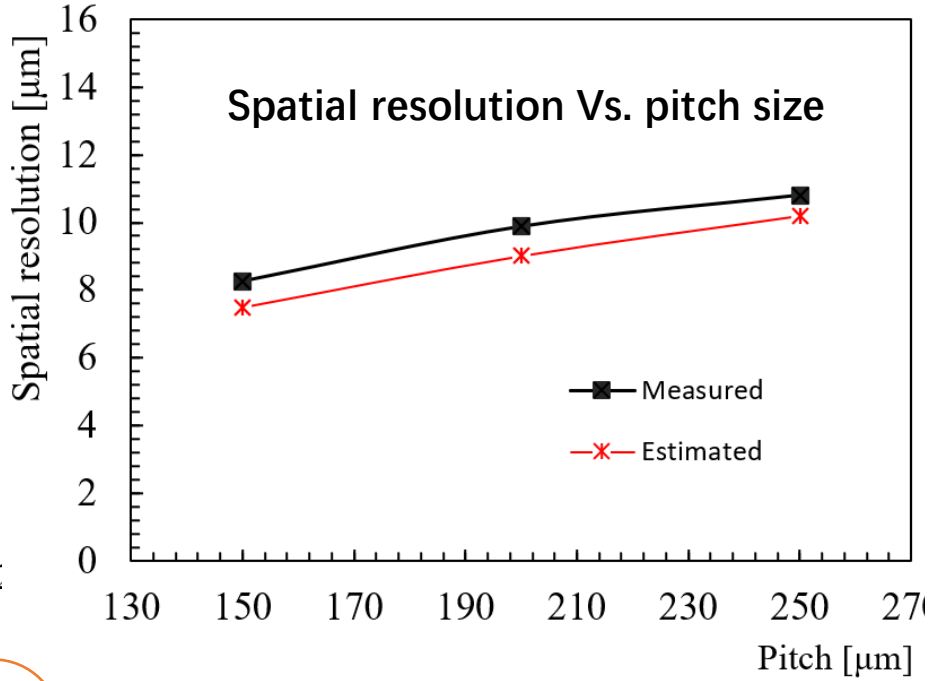

**Position reconstruction:**

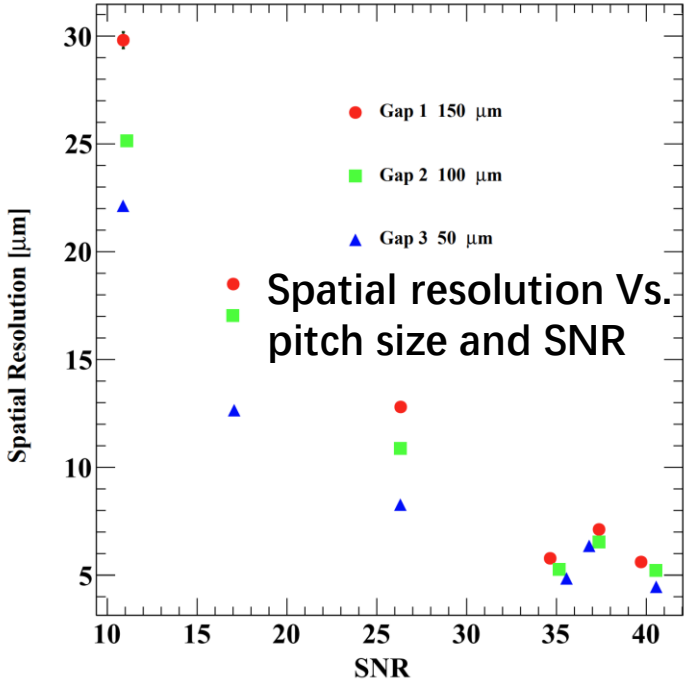
- The fraction of the signal (*R*) changes linearly with the movement of the laser.

- Good consistency between the reconstruction position and the laser position
- The smaller the pitch size, the better the spatial resolution

# 6. Spatial resolution




**Resolution estimation:**

$$\sigma_{spatial} \approx \frac{N}{A}$$

*A*: signal attenuation factor

*N*: noise RMS (sensor + electronics)

- N+ dose 10 P→0.2 P, spatial resolution 36 -> 16 μm.
- **Lower N + dose** has higher resistivity and larger attenuation factor, ->**better spatial resolution**.
- **Smaller pitch sizes** result in faster signal attenuation and larger attenuation factor, ->**better spatial resolution**
- **SNR 10→40, s.r. 22/30→5μm**

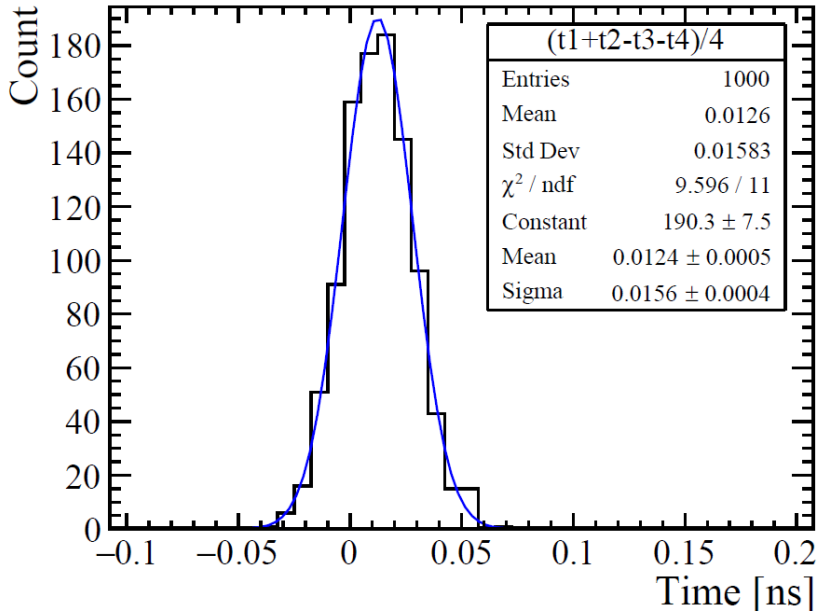
- **Spatial resolution can also be evaluated according to signal attenuation factor and noise level.**
- **In principle, the effect of pitch size on spatial resolution will be eliminated, and the resolution can be further improved.**



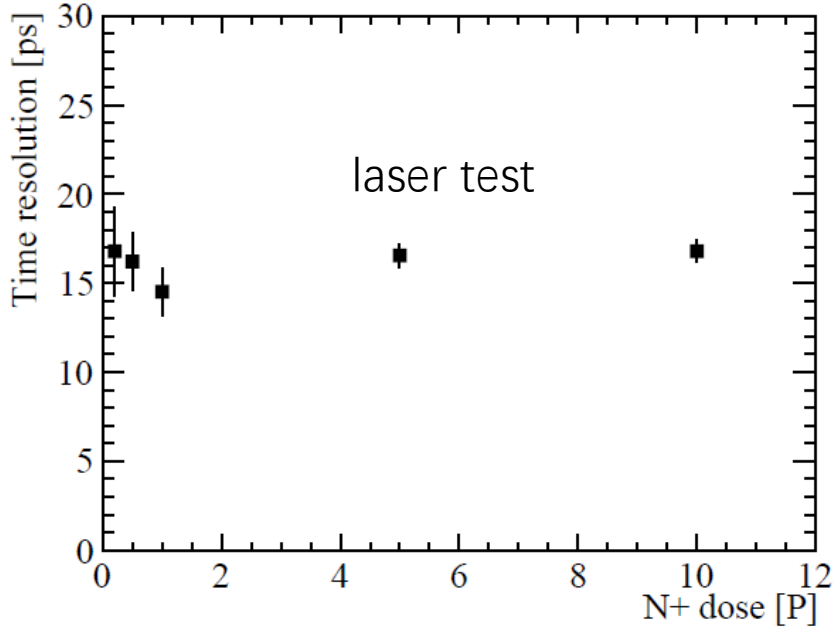
*The Performance of Large-Pitch AC-LGAD With Different N+ Dose, IEEE TNS 70(8) 2023*

# 7. Timing resolution of Pixel LGAD

Timing resolution @ 0.5P



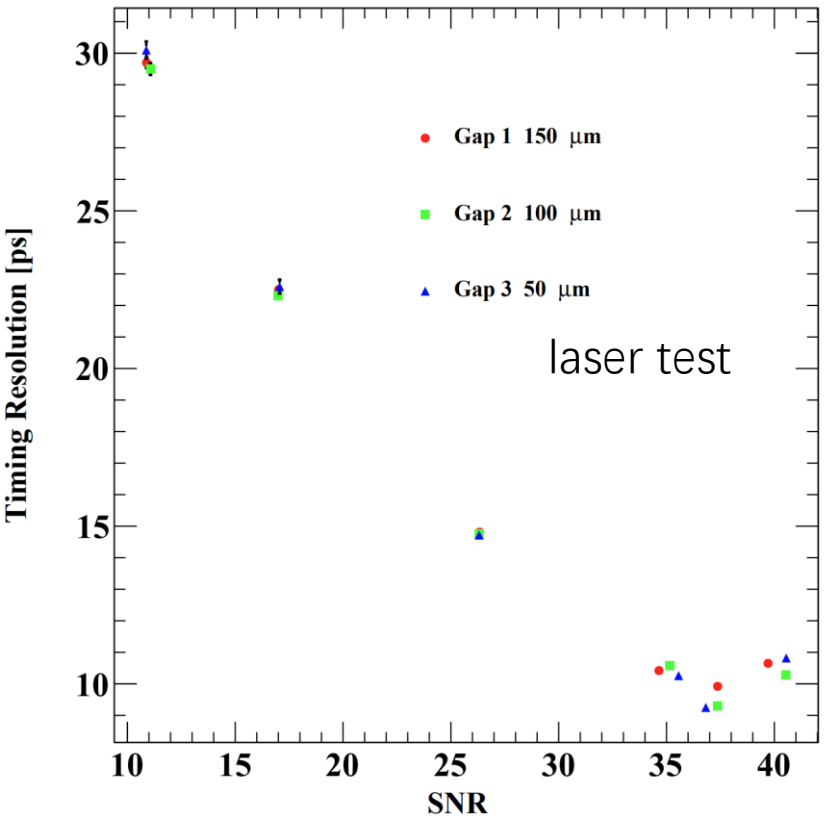

Timing resolution Vs. N+ dose

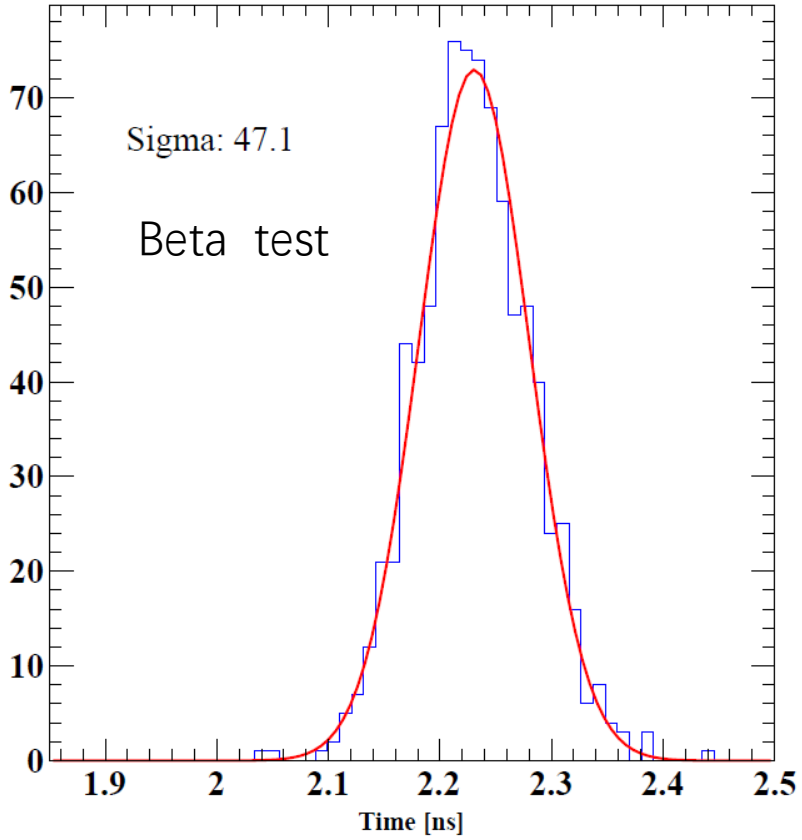



- No significant change in timing resolution was demonstrated over the injected dose range of 0.2-10.0P.
- The timing resolution obtained from the laser test contains only the jitter term and not the Landau term.
- ~15 ps, via laser test

$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{Landau}^2 + \sigma_{Jitter}^2$$

# 7. Timing resolution of Strip LGAD




Timing resolution of Trigger

$$\Delta T = T_{trigger} - \frac{\Sigma_i a_i^2 T_i}{\Sigma_i a_i^2}$$

Difference between Trigger and reconstructed

Weighted timing resolution of three strip electrodes

$$\sigma_{Strip}^2 = \sigma_{\Delta T}^2 - \sigma_{Trigger}^2$$

**Timing Resolution**

**37.5 ps**

- **No significant change in timing resolution was observed among different pitches**
- **Timing resolution improves as increasing in SNR, same trend as in spatial resolution**
- **Saturation may be observed, ~ 10 ps.**
- **47.1 ps timing resolution, via Beta test.**

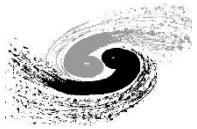
*Characterisation of Spatial and Timing Resolution of IHEP AC-LGAD Strip arXiv:2307.03894*

# 8. Summary

- AC-LGAD is a new 4D detector （position + time）
- IHEP has designed pixels and strips AC-LGAD sensors
- **The best spatial resolution of pixel and strips AC-LGAD ~16 μm ~8μm**
- **Low N+ dose and small pitch size have better spatial resolution**
- **The signal attenuation factor and noise level are the main parameters for estimating the spatial resolution**
- **SNR is vital in both spatial and timing resolution, further improvement may be made by improving of SNR**

**The next plan of IHEP AC-LGAD**

- Test beam
- Optimize n+ p+ layers and AC-electrodes
- Advanced algorithms for the reconstruction
- Ultra Low Noise Electronics
- ASIC and monolithic integration
- ……



Thanks